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# CRYSTALLOBLASTIC ORDER AND MINERAL DEVELOPMENT IN METAMORPHISM

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## VARIATIONS IN DEGREE OF METAMORPHISM

Metamorphic rocks often exhibit, within the same region, considerable variation in the kind and especially in the amount of metamorphism to which they have been subjected. This is particularly true of intrusive contact zones where a more or less uniform decrease in metamorphism may be observed away from the intrusive body.<sup>1</sup> In regional metamorphism, too, gradations may be found in the degree of alteration of the crystalline schists; but the variations here are much less regular than in the former case.

Recognizing the fact that long duration of time is an essential requisite for the course of metamorphism,<sup>2</sup> we may assume that a metamorphic rock, whatever may have been the forces concerned in its origin, must have passed through a sequence of stages of

<sup>1</sup> See A. Geikie, *Textbook of Geology*, 4th ed. (1903), p. 773; G. Barrow, "On an Intrusion of Muscovite-biotite Gneiss in the Southeastern Highlands of Scotland, and Its Accompanying Metamorphism," *Quar. Jour. Geol. Soc. Lond.*, XLIX (1893), 330.

<sup>2</sup> Grubenmann lays emphasis on the great importance of time. He writes, "Die Temperatur darf wohl als der bedeutendste Faktor der Metamorphose betrachtet werden."—*Die Kristallinen Schiefer*, 2d ed. (1910), p. 51.

development leading up to its present form; and we may assume further that, in any given region, provided we consider only rocks which were once of similar nature, this sequence of stages is represented, in a general way, by a graded series from the least altered to the most altered specimens. Within the writer's personal observation the best area illustrating such variations, in the case of regional metamorphism, is the Narragansett Basin in southern Rhode Island.

#### STAGES OF METAMORPHISM IN SCHISTS OF THE NARRAGANSETT BASIN

The Narragansett Basin is a structural basin consisting of a downfolded and downfaulted block of Carboniferous mudstones, sandstones, and conglomerates of fresh water deposition. These strata were folded and were altered by dynamic and static metamorphism during the Appalachian Revolution. They appear to have been near enough alike in their original state to justify a comparison of them now.

The characters of these rocks, as investigated by the writer,<sup>1</sup> led him to group them, according to their degree of metamorphism, in four stages, designated A, B, C, and D. "The metamorphism is incipient in Stage A; distinct, but rather low, in Stage B; considerable to high in Stage C; and at a maximum in Stage D."<sup>2</sup>

The criteria used in distinguishing between these stages were: amount of granulation or distortion of clastic components; deformation of pebbles, fossils, and such original structures as cross-bedding, ripple-mark, etc.; proportion of new or metamorphic minerals; proportion of recrystallized components; shape of mineral grains; mode of aggregation of constituents; degree of parallelism of minerals with unequal dimensions and of elongate mineral aggregates; perfection of rock cleavage (fracture); and gloss on fracture surfaces of the rock.

<sup>1</sup> F. H. Lahee, "Relations of the Degree of Metamorphism to Geological Structure and to Acid Igneous Intrusion in the Narragansett Basin, R.I.," *Am. Jour. Sci.*, (4), XXXIII, 249, 354, 447.

<sup>2</sup> *Ibid.*, p. 355.

Briefly the characters of the four stages may be summarized as follows:

*Stage A:*

*Megascopic*.—Fracture of rock irregular, or there may be a tendency to break parallel to the bedding. The fracture surfaces are dull. Original structures, fossils, and pebbles are not deformed.

*Microscopic*.—Nearly all the constituents are of clastic origin, with clastic outlines. Sericite, the first metamorphic mineral to appear, may be present in small quantity. There is no parallel alignment of elongate or flat minerals, unless parallel to the bedding, and then this arrangement is primary.

*Stage B:*

*Megascopic*.—There is a fair secondary cleavage. The cleavage surfaces have a faint gloss due to the parallel orientation of microscopic blades of sericite. Original structures, fossils, and pebbles may be somewhat distorted.

*Microscopic*.—Clastic grains are bent, strained, or crushed. Quartz grains may be granulated about their edges, or in bands that cross them, or entirely, and in the latter case the aggregates of grains may have been pressed out into lenticular form. Sericite is more abundant than in Stage A and a large proportion of it has parallel orientation. It is the principal cleavage-maker. Pebbles in conglomerate are thinly coated with this mica.

*Stage C:*

*Megascopic*.—The secondary cleavage is very good and the fracture surfaces have a brighter gloss. Fossils are usually unrecognizable. Pebbles may be much flattened or elongated. Original structures have been obscured or destroyed. Metacrysts<sup>1</sup> begin to be of marked importance.

*Microscopic*.—Much of the crushed clastic quartz has been recrystallized, the new grains being somewhat elongate parallel to the schistosity. Feldspar of secondary origin is occasionally seen. Sericite is very abundant and may show signs of growing coarser, to muscovite.<sup>2</sup> Its plates and laths lie approximately parallel. In the conglomerates sericite may be observed developed within the pebbles, but most other new minerals occur in the paste only. The mica coatings of the pebbles are thicker.

*Stage D:*

*Megascopic*.—A thin, perfect cleavage characterizes the rock. There may be a false cleavage. Fracture surfaces have a high sheen. Original structures are much deformed. Pebbles are either sheet-like or spindle-shaped, much longer than they are thick. No sign of fossils can be discovered.

<sup>1</sup> The name "metacrystals" was proposed by Lane for phenocrysts in metamorphic rocks, these crystals being of later origin than the groundmass (A. C. Lane, "Studies of the Grain of Igneous Intrusives," *Bull. Geol. Soc. Am.*, XIV [1903], 369).

<sup>2</sup> Grubenmann, *op. cit.*, p. 86.

*Microscopic.*—All the quartz is secondary. It often occurs in long thin blades and in thin plates parallel to the schistosity. Sericite has given place largely to muscovite. There is extreme parallelism of the constituents which are clear and free from indications of strain. The metamorphic (secondary) minerals are as abundant in the pebbles as in the paste. Recrystallization in pebbles and paste is at a maximum.

#### STUDY OF THE METACRYSTS

Many of the fine-grained schists of the last three stages contain metacrysts, or pseudophenocrysts, of ilmenite, biotite, garnet, and

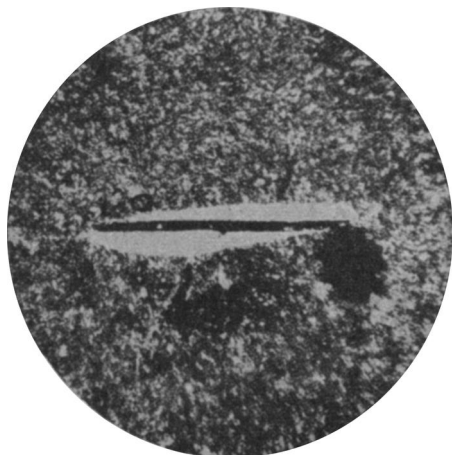


FIG. 1.—Crystal of ilmenite sandwiched between layers of secondary quartz. 15 diameters.



FIG. 2.—Metacrysts of biotite and ilmenite in a rock with poor flow cleavage. (See Fig. 3.) 15 diameters.

ottrelite, named in order of decreasing frequency. The same minerals are found in some of the coarser rocks, but in these they are no longer conspicuous for their relatively large size. The relations of these four minerals to one another and to the schistosity in the different stages of metamorphism will be described herein in greater detail than was possible in the earlier paper on this subject.<sup>1</sup>

*Ilmenite.*—In rocks of Stage B metacrysts of ilmenite occur as tabular crystals, thin or thick as the case may be (see Figs. 1, 2,

<sup>1</sup> F. H. Lahee, *op. cit.*

and 3).<sup>1</sup> When examined under the microscope they are quite opaque. Occasionally they contain small inclosures of quartz and sericite, the principal constituents of the groundmass, and their edges are more or less serrate where they have grown against these minerals. Since ilmenite is not a silicate, it evidently made room for itself by replacing the minerals of the groundmass and not by absorbing them. Its efficiency of replacement must be high for it contains relatively few inclusions.<sup>2</sup>

Where the groundmass has no parallel arrangement of its constituents and even where it does possess a flow cleavage that is

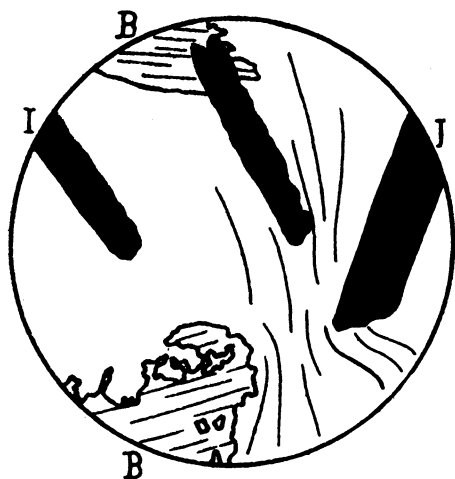


FIG. 3.—Outline sketch of Fig. 2. Ilmenite crystal partly inclosed in biotite. Note curving of the schistosity. I, ilmenite. B, biotite.

not too well marked, the ilmenite plates lack definite orientation. Fig. 2 illustrates a portion of a rock slide in which the ilmenite crystals were scattered at random and the schistosity curved round them. It is evident here either (1) that they developed before the flow cleavage and that, in this case, the shearing of the rock was not sufficiently rapid or strong to bend or break them; or (2) that they grew *pari passu* with the schistosity, but

that the shearing force was not enough to prevent their random orientation, that is, that their molecular forces were greater than the exterior stress. In either event they may have suffered some rotation.

<sup>1</sup> The photomicrographs used for this article were taken by Professor E. C. Jeffrey of Harvard University. The writer is happy to express his deep gratitude to Professor Jeffrey for this compliment and for valuable suggestions in preparing the illustrations.

<sup>2</sup> Cf. Van Hise, "In proportion as minerals are unable to absorb, they are able to enclose."—*Treatise on Metamorphism, U.S.G.S. Monog.*, XLVII (1904), 700.

In many of the finer mud schists the plates of ilmenite are coated with quartz<sup>1</sup> (see Fig. 1). The correct explanation for this phenomenon is not certain. The suggestion has been made that the quartz-ilmenite aggregate occupies a space which was formerly an actual cavity or a potential one. This does not seem to be true, for the space has not the shape of a rent, and neither the ilmenite nor the quartz granules of the rim reveal any evidence of having grown inward from the walls of a cavity. The form of the present quartz-ilmenite aggregate indicates that it is a replacement of an earlier larger crystal of ilmenite or of some other flat mineral.

In rocks with a good flow cleavage, produced both by thin plates of recrystallized quartz and by sericite (Stages C and D), the ilmenite crystals are parallel to the schistosity (see Figs. 4 to 8). It is not at all likely that the ilmenite here originated before shearing, for rotation could not account for the nearly exact parallelism of all the plates in the rock. Two possibilities remain, then: that the building of its crystals was either contemporaneous with, or subsequent to, the origin of the schistosity. If the first condition was the actual one, the ilmenite as well as the quartz and sericite contributed to the accommodation of the rock to the stress, the accommodation being brought about by crystallization and recrystallization, i.e., by chemical processes. If, on the other hand, the second condition was the real one, the ilmenite plates did not contribute toward the accommodation, but acquired their parallelism on account of a property of the groundmass constituents (principally quartz and sericite) to dissolve more readily parallel to the schistosity than in any other direction. Now, it is known that

<sup>1</sup> Ilmenite has been described by Wolff and Pumpelly as bordered by chlorite; by Renard as bordered with sericite; and by Williams as coated by biotite. See the following:

A. Renard, "Recherches sur la composition et la structure des phyllades ardennais," *Bull. Mus. R. His. Nat. Belg.*, I, 212; II, 127; III, 84, 230 (1884).

G. H. Williams, "The Greenstone Schist Areas of the Menominee and Marquette Districts," *Michigan U.S.G.S., Bull.* 61 (1890), 200.

J. E. Wolff, "On Some Occurrences of Ottrelite and Ilmenite Schists in New England," *Bull. Harv. Mus. Comp. Zool.*, XVI, 8 (1890), 162.

R. Pumpelly, J. E. Wolff, and T. N. Dale, "Geology of the Green Mountains in Massachusetts," *U.S.G.S. Monog.*, XXIII (1894), 183.



FIG. 4.—Ilmenite and biotite meta-crysts in a rock having good flow cleavage. 15 diameters.

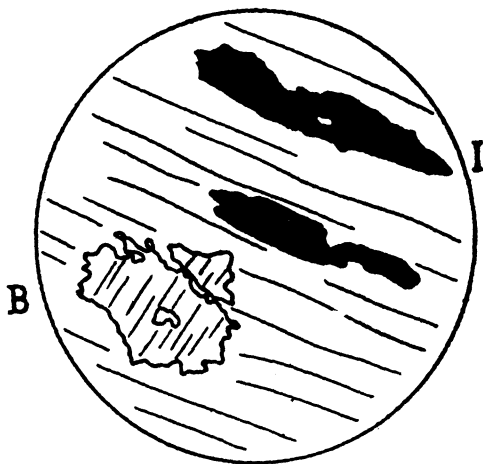


FIG. 5.—Outline sketch of Fig. 4. The ilmenite crystals lie parallel to the schistosity. One of them and the biotite contain inclusions of quartz. The irregularities of both ilmenite and biotite are due to growth of these minerals against the constituents of the groundmass.

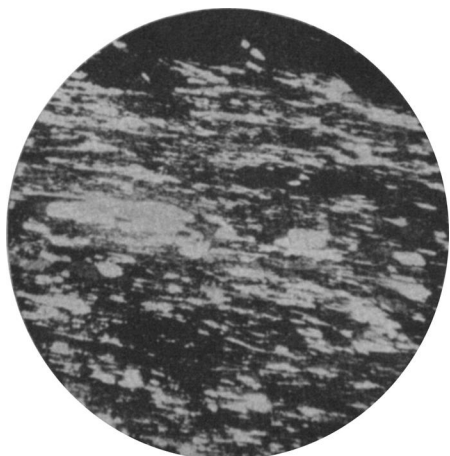


FIG. 6.—Photomicrograph of a rock belonging to "Stage D." The quartz is all secondary. The schistosity is well developed. An ilmenite lath with two quartz inclusions lies parallel to the schistosity. (See Fig. 7.) 10 diameters.

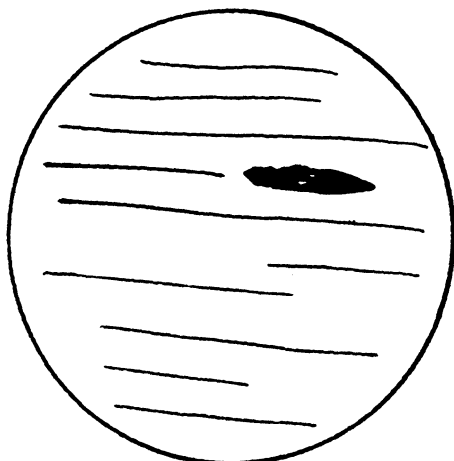


FIG. 7.—Outline sketch of Fig. 6. Shows position of the ilmenite crystal, and its relation to the flow cleavage.

the facility of solution and crystallization varies in different crystallographic directions and for different crystal forms of the same substance;<sup>1</sup> but, while this property might be suggested to explain the replacement of sericite, it could not account for the replacement of quartz, because quartz does not have crystallographic parallelism. Quartz plates would not tend to dissolve more readily at their edges than on their broad surfaces. If the rule applied to sericite only, and not to quartz, we should expect to find evidence of selective replacement by the ilmenite—substitution of sericite and not of quartz. However, no such evidence is apparent. The necessary conclusion is that the ilmenite plates, like the sericite and quartz, were formed during the operation of the shearing stress.<sup>2</sup>

The relations of the growth of ilmenite to the development of the schistosity are brought out in Figs. 9 to 12. Figure 9 exhibits a garnet grain (about 1/16 inch in diameter) which partly inclosed an ilmenite crystal. The portion of the ilmenite outside the garnet is about half as thick as that inside and lies parallel to the schistosity which wraps round the garnet. The events illustrated by the photograph seem to have been as follows: (1) growth of a relatively thick plate of ilmenite; (2) inclosure of part of this plate by a crystal of garnet; (3) shearing of the rock, which produced, in the ground-mass, a schistose structure that curves round the garnet, and



FIG. 8.—Similar to Fig. 6. An ilmenite lath may be seen near the top of the figure. The flow cleavage has been somewhat folded, thus showing a tendency toward the formation of a false cleavage. 20 diameters.

<sup>1</sup> See writings by Goldschmidt and others.

<sup>2</sup> Van Hise states that no minerals show crystallographic orientation under mass-static conditions (*op. cit.*, p. 689). When minerals are crystallographically, as well as dimensionally, oriented, the suggestion derived from Goldschmidt's work should receive careful consideration.

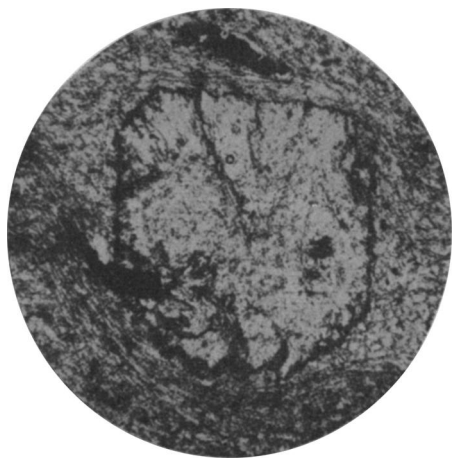


FIG. 9.—A large garnet grain partly inclosing an ilmenite lath which has been bent into parallelism with the schistosity. (See Fig. 10.) 15 diameters.

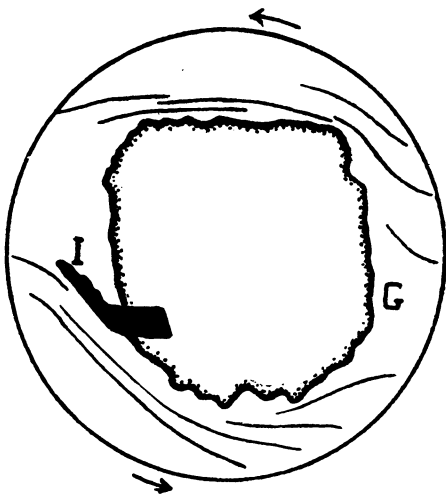


FIG. 10.—Outline sketch of Fig. 9. The schistosity, shown by curving lines, wraps round the garnet grain. The position and shape of these curves indicates that the garnet was rotated (arrows). G, garnet. I, ilmenite.



FIG. 11.—Ilmenite bent and inclosed in garnet. (See Fig. 12.) 25 diameters.

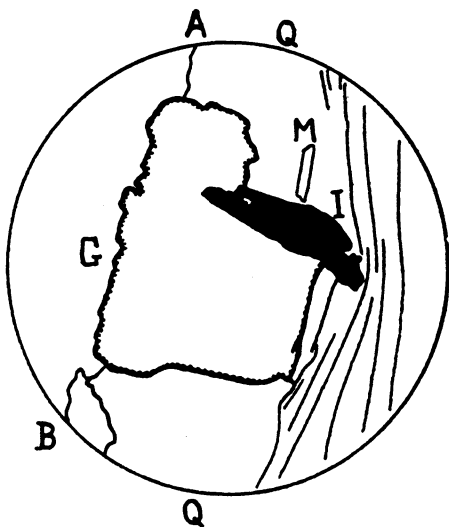


FIG. 12.—Outline sketch of Fig. 11. M, muscovite. Q, quartz. Between A and B is the edge of the rock section, under the cover glass.

resulted in the thinning of the protruded part of the ilmenite and in its being bent into parallelism with the adjacent schistosity. Since the ilmenite reveals no sign of fracture at its "elbow of deformation," its distortion was probably accomplished by gliding or by less regular molecular readjustment. In either case the facility of adjustment in the ilmenite must have been at least as great as the ease of accommodation of the groundmass; i.e., deformation of the ilmenite must have kept pace with development of the schistosity.

Fig. 11 shows a similar instance of an ilmenite crystal partly inclosed by garnet, but here the projecting portion of the ilmenite is less bent and less thinned than in the preceding example. A small re-entrant at the elbow of deformation, now filled with secondary quartz, suggests that the shearing produced a small fracture, subsequently perhaps more or less restored, or—and this is more probable—that it locally increased the tendency toward molecular readjustment at that place, making the ilmenite susceptible to replacement by quartz.<sup>1</sup>

*Garnet.*—Garnet metacrysts are found in rocks assigned to Stages C and D. In all cases there is clear evidence that this mineral originated before shearing entirely ceased.<sup>2</sup> Figs. 9 to 12 bring out this feature very well. The structure of the groundmass, particularly in Figs. 9 and 10, indicates rotation of the garnet crystal, and a similar relation appears in Figs. 13 and 14. Fig. 13 shows also the so-called "tails" of quartz, light areas that extend in opposite directions a short distance out from the metacryst, parallel to the schistosity. Such "tails" are without doubt in process of formation during the shearing of the rock. Consequently, their peculiar association with the garnet metacrysts is another fact pointing to the conclusion that the garnet was formed before the cessation of mechanical deformation.

*Biotite.*—As would naturally be expected, in rocks with no flow cleavage, biotite plates, if present, have no definite orientation.

<sup>1</sup> "The experimental work of Barus and Hambeuchen together has completely demonstrated that a state of strain in substances is favorable to chemical action."—Van Hise, *Treatise on Metamorphism*, p. 691.

<sup>2</sup> Cf. this statement by Leith: Garnet, staurolite, andalusite, etc., "in many if not in most cases crystallized out later than the principal cleavage-making minerals. . . ."—C. K. Leith, "Rock Cleavage," *U.S.G.S., Bull.* 239 (1905), 93–94.



FIG. 13.—Garnet crystal in schist. (See Fig. 14.) 15 diameters.

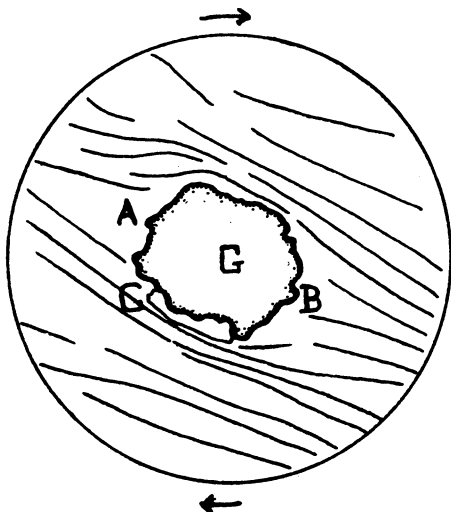


FIG. 14.—Outline sketch of Fig. 13. C, chlorite. A and B, the poles of minimum compression. The quartz "tails" extend out from the garnet (G) from these poles in opposite directions. The curves of the schistosity indicate rotation of the garnet (arrows).



FIG. 15.—Metacrysts of biotite in a rock having no flow cleavage. The irregular outlines of the metacrysts are determined by the adjacent quartz grains. The biotite has neither dimensional nor crystallographic orientation. 12 diameters.



FIG. 16.—Photomicrograph of a rock with a well-developed flow cleavage. The biotite plates (dark) have dimensional parallelism and many of them have crystallographic parallelism. 10 diameters.

This is illustrated in Fig. 15. The biotite is here mottled lighter and darker. The light portions were once quartz grains of the groundmass, which were absorbed or replaced by the mica in its growth. The dark areas contain a large proportion of opaque carbonaceous matter which was also a part of the groundmass and which was included, but not absorbed nor replaced. For this reason the structure of the groundmass is nearly as distinct within these biotite crystals as it is outside. Their edges, like those of the ilmenite plates, are irregular because of their growth against constituents of the groundmass, and the white inclusions and re-entrants are unabsorbed quartz grains.

In schists belonging to Stage C, in which ilmenite has already acquired parallel orientation and much of the quartz of the groundmass bears evidence of recrystallization, biotite still lacks dimensional and crystallographic parallelism. The biotite crystal photographed in Fig. 4 was cut where a quartz band passes quite through it. Its cleavage is nearly perpendicular to the schistosity and its length is only very little greater than its width.

Under conditions of extreme metamorphism (Stage D), biotite acquires dimensional parallelism (Fig. 16). At this stage the quartz of the rock is of secondary origin and the sericite, the earliest new mineral to appear at the inception of metamorphism, has given place to muscovite. Crystals of these three minerals are roughly of the same size. The quartz and white mica have become relatively larger, and the biotite has become relatively smaller.

Several slides show that the biotite was subsequent to the ilmenite in respect to its origin. In Figs. 2 and 17 biotite crystals have partly inclosed adjacent plates of ilmenite. The projecting ends of the ilmenite in Fig. 17 (see also Fig. 18) have quartz borders like those illustrated in Fig. 1. This quartz border, once entirely surrounding the ilmenite, was absorbed or replaced by the biotite in just the same way as the quartz grains of the groundmass, as shown in Fig. 15. This is the explanation of the light halo that encircles the included portion of the ilmenite.<sup>1</sup>

<sup>1</sup> Professor Wolff describes a rock in which ilmenite plates are coated with chlorite except where they are included in ottrelite (J. E. Wolff, "On Some Occurrences of Ottrelite and Ilmenite Schist in New England, *Bull., Harv. Mus. Comp. Zool.*, XVI, 8 [1890], p. 162).



FIG. 17.—Ilmenite crystal nearly inclosed in biotite. (See Fig. 18.) 12 diameters.

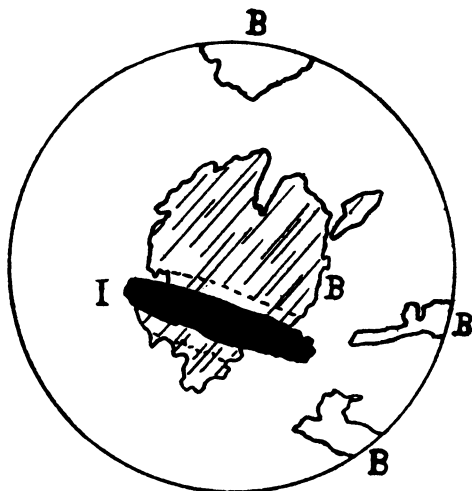


FIG. 18.—Outline sketch of Fig. 17. B, biotite. I, ilmenite. The dotted lines represent the edge of what used to be a quartz coating on the ilmenite. Cf. Fig. 1.



FIG. 19.—Biotite and garnet metacrysts. (See Fig. 20.) 25 diameters.

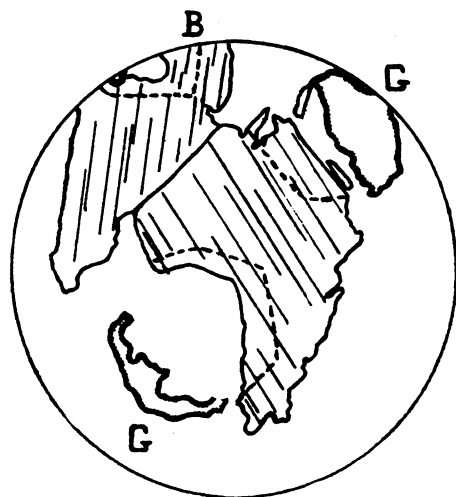


FIG. 20.—Outline sketch of Fig. 19. B, biotite. G, garnet. The dotted lines represent the edges of the garnet crystals before replacement by biotite.

Fig. 19 shows a large biotite plate which has replaced a portion of a garnet crystal. The hexagonal outline of the cross-section of the latter is plainly visible in the mica. Between the biotite and the outlying strip of garnet (Fig. 20) is a clear space occupied chiefly by secondary quartz and muscovite. Two or three minute grains of garnet in this space suggest that this mineral once existed as a complete crystal which was replaced partly by biotite and partly by the quartz-muscovite aggregate.<sup>1</sup> Obviously, biotite developed after garnet.

*Ottrelite*.—Although ottrelite (Fig. 21) was seen only in rocks with a good flow cleavage, its crystals were never observed to have dimensional parallelism. Leith states, however, that it may occasionally show a definite orientation.<sup>2</sup> Plates of this mineral sometimes wholly or partly include metacrysts of ilmenite and biotite. Ottrelite, then, originates later than ilmenite, garnet, and biotite, and as a rule subsequent to the development of the schistosity.

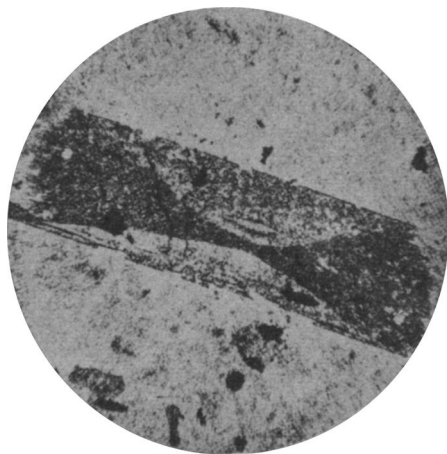


FIG. 21.—Metacryst of ottrelite showing hour-glass twin. 25 diameters.

#### SUMMARY AND CONCLUSIONS

The facts presented in the foregoing description of microscopic structures in the Narragansett Basin schists may be summarized as follows:

1. The commonest minerals in these rocks are sericite, muscovite, quartz, ilmenite, garnet, biotite, and ottrelite. Quartz and sericite or muscovite form a large percentage of the composition of

<sup>1</sup> Cf. B. K. Emerson on "skeleton crystals" of garnet: "Note on Corundum and a Graphite Essonite from Barkhamsted, Connecticut," *Am. Jour. Sci.* (4), XIV (1902), p. 234.

<sup>2</sup> "Rock Cleavage," *U.S.G.S., Bull.* 239 (1905), p. 44.

each rock. They may occur as a relatively fine groundmass in which ilmenite, biotite, garnet, and ottrelite may be present as metacrysts.

2. Minerals that crystallize or recrystallize with parallel orientation promote the accommodation of the rock to the stress.<sup>1</sup>

3. A mineral that is shown to acquire parallel orientation at an *early* stage of dynamic metamorphism will grow with parallel orientation in later stages, provided shearing continues.

4. A mineral that acquires parallel arrangement at a *late* stage of dynamic metamorphism may develop at an earlier stage, but in this case it originates after shearing has ceased and then has no definite orientation.

5. In the Narragansett Basin schists sericite is the first metamorphic mineral to appear and is the first to acquire definite orientation of its crystals under conditions of stress. In Stage D it may give place to muscovite.

6. Quartz is chiefly clastic in the early stages of metamorphism and secondary (recrystallized) in the later stages. In the accommodation of the rock to stress it assists first by granulation and later by recrystallization. It acquires dimensional, but not crystallographic, parallelism in Stages C and D.

7. The order in which the minerals acquire both dimensional and crystallographic parallelism, beginning with the earliest, is as follows: sericite, ilmenite, biotite, ottrelite. Secondary quartz, having only dimensional parallelism, would come between ilmenite and biotite.<sup>2</sup>

8. The order of origin of the metacrysts, as shown by their relations to one another, is: ilmenite (first), garnet, biotite, and ottrelite. Grubenmann calls this a crystalloblastic order (*Reihe*).<sup>3</sup> He gives the following succession for minerals of metamorphic origin: titanite, rutile, hematite, ilmenite, garnet, tourmaline,

<sup>1</sup> Cf. Leith: "Minerals showing the best evidence of recrystallization are those best adapted by their shape and dimensions to conditions of unequal pressure," *op. cit.*, p. 95.

<sup>2</sup> Leith places quartz after the micas in respect to its cleavage-making capacity. Commencing with the best cleavage-maker, his order is: micas, hornblende, quartz, and feldspar (*op. cit.*, p. 64).

<sup>3</sup> *Die kristallinen Schiefer*, p. 91.

staurolite, cyanite—epidote, zoisite—pyroxene, hornblende—magnetite, dolomite, albite, mica, chlorite, talc—calcite—quartz, plagioclase—orthoclase, microcline. In general the series is one of decreasing specific gravity and of increasing molecular volume.<sup>1</sup> It is interesting to compare Grubenmann's values for specific gravity and molecular volume<sup>2</sup> for the four minerals under discussion. They are:

|                                  | Sp. gr. | Mol. vol. |
|----------------------------------|---------|-----------|
| Ilmenite . . . . .               | 4.70    | 31.7      |
| Garnet (almandite) . . . . .     | 4.11    | 119.8     |
| Biotite . . . . .                | 3.06    | 152.2     |
| Ottrelite (chloritoid) . . . . . | 3.50    | 69.6      |

Ottrelite is an exception to Grubenmann's generalization.

Mention may be made here of other references to crystalloblastic order. Wolff<sup>3</sup> has shown that ottrelite may crystallize out before ilmenite. According to F. W. Clarke,<sup>4</sup> andalusite, sillimanite, and kyanite originate in the order named, with increasing metamorphism. This has been recorded by several observers. Van Hise<sup>5</sup> states that garnet represents a less advanced stage of alteration than staurolite. Where both of these minerals occur in the same schist garnet is frequently inclosed in staurolite. The present writer has seen this in many of the New Hampshire schists. Leith<sup>6</sup> writes: "We know definitely that quartz generally crystallizes before feldspar, and mica and hornblende before quartz and feldspar. . . . Muscovite and biotite, when they occur together, usually develop simultaneously. . . . Exceptionally the muscovite evidently crystallizes before the biotite." Garnet and staurolite are listed by Leith with the minerals that crystallize out after the cleavage-making minerals.

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<sup>1</sup> *Op. cit.*, pp. 91-92.

<sup>2</sup> *Op. cit.*, pp. 54-55.

<sup>3</sup> J. E. Wolff, "On some Occurrences of Ottrelite and Ilmenite Schist in New England," *Bull. Harv. Mus. Comp. Zool.*, XVI, 8 (1890), p. 163.

<sup>4</sup> "Data of Geochemistry," *U.S.G.S., Bull.* 330 (1908), p. 528.

<sup>5</sup> C. R. Van Hise, *Treatise on Metamorphism*, p. 903.

<sup>6</sup> *Rock Cleavage*, pp. 93-94.